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SOLAR PROTONS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON July 1962

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SUMMARY

In recent years, especially since the International Geophysical Year, a good deal of attention has been given to experimental studies of particles accelerated by the sun during solar flares. This lecture examines the state of experimental knowledge and the methods used to study solar protons. An account is given of the results of rocket observations carried out by NASA during the November, 1960, events. Since the lecture was given, more analysis has been carried out, but this has only served to add to the material presented, not to alter it.

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INTRODUCTION

There have been several well known instances of the acceleration by the sun of cosmic ray particles which have been detected at sea level by the traditional methods: the neutron monitor and the meson telescope. It was at one time suggested that this was a very unusual property of solar flares, and indeed that extremely large chromospheric disturbances and unusual conditions near the sun were required to accelerate particles and to allow them to escape. At the present time it is thought that cosmic ray particles, principally protons, are accelerated and escape from the sun much more often than was formerly thought, but that their energy spectrum is such that they can usually be detected only by their effects at high altitudes and high latitudes. Not every class 3+ solar flare is followed by such a "solar beam" interacting with the earth and this situation makes the problem of the solar beam an attractive one, having ramifications which lead far from the traditional areas of cosmic ray research.

RADIO OBSERVATIONS

Radiation from the galaxy as a whole must pass through the ionosphere to reach the earth. Since the time scale of galactic changes is longer than that of solar system changes the radio output of the galaxy does not appear to change with time, and therefore observations of the signal strength can show variations which are characteristic of the ionosphere. If a plane wave is incident upon the ionosphere, after traveling a distance d,

$$E_d = E_0 e^{-Kd} ,$$

and the absorption in db is

$$A = 20 \log_{10} \frac{E_0}{E_d} .$$

*A lecture given at the Scuola Internazionale di Fisica "Enrico Fermi", Varenna sul Lago di Como, Course on Cosmic Radiation, Solar Particles and Space Research, May, 1961.

†NAS-NASA postdoctoral research associate.

For a single passage of the ionosphere

$$A = 20 \int KS$$

$$K = \frac{2\pi e^2}{mc} \frac{1}{\mu} \frac{N\nu}{\nu^2 + (\omega + \omega_L)^2}$$

where N = electron density, ω = frequency, μ = index of refraction, ω_L = gyro frequency, and ν = collision frequency.

If $\mu = 1$ and $\nu < (\omega \pm \omega_L)$ at high altitude, then $A = \frac{k}{\omega^2} \int N\nu dl$. The time constants of the processes are such that equilibrium can be safely assumed at all times. Thus, the absorption in the ionosphere is proportional to $\frac{1}{\omega^2}$ and to $\int N\nu dl$. If the variation of N with height and also the variation of ν with height is known, then the absorption can be calculated. The electron density is here supposed to be due to particles traveling in the earth's field, and incident primarily at high latitudes because of this field. However, the variation of N with height obviously depends upon the energy spectrum, and furthermore the collison frequency as a function of height is not a well known quantity, so the exact height at which the maximum of absorption takes place is still subject to some doubt.*

An idea of the sensitivity of the absorption can be gained from a rough calculation which shows that the method can detect protons equal to 10 times the normal cosmic ray background incident on the upper hemisphere with energies greater than 100 Mev at 65 degrees geomagnetic latitude. The instrument produced by Little and Leinbach (Reference 3) to measure ionospheric absorption using these principles is called a riometer.

Ionospheric absorption can thus detect the incidence of particles which could never make themselves felt at the ground. The riometer was first made to study the auroral absorption which is such a nuisance to radio communication in the north. It was noticed that a few hours after large solar flares the instrument often shows a characteristic slow increase in absorption, eventually reaching a maximum which subsequently decays over a period of several days. During this time a normal ionosonde, which operates at a much lower frequency and requires a double passage of the ionosphere, is completely "blacked out". The absorption gradually disappears, and during the latter part of the time, after the sudden commencement of the geomagnetic storm, strong auroral absorption is superimposed. The large value of the absorption observed on some occasions (greater than 15 db at 27 Mc/sec), and the strong latitude dependence indicate a large flux of low energy particles, an obvious field for study by traditional cosmic ray methods.

*A comprehensive calculation on the variation with height of the absorption as a function of latitude and energy spectrum, based on the best values for the collision frequency has been published by Brown and Weir (Reference 1), and by Reid (Reference 2).

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Figures 1 and 2, show two records of recent events. The most obvious feature of these is the nighttime recovery of signal strength. This is a local effect caused by the attachment of free electrons. During the day, the incident radiation can detach these electrons, but after sunset at the height of the absorbing layer, about 50 km, they are not available to load the radio waves. The most likely candidate for the attaching molecule is 0_2 but NO may play a part (Reference 4). In a calculation using a simple trial spectrum, Bailey (Reference 5) reproduced this day-night effect, predicting a ratio of about 6 to 1 for the absorption (see also Reference 2).

In practice, differentiation between polar cap absorption (P.C.A.), as this effect is called, and auroral absorption is not difficult, but in any case propagation by tropospheric scatter is immune to auroral absorption (Bailey, private communication) as the scattering takes places in the D layer.

As was mentioned previously, a normal ionosode shows blackout conditions during a P.C.A. event. Now the riometer observations do not go back in time beyond 1957, so that statistics of time variations are poor. These can be improved by using periods of ionosonde blackout, with the further advantage that ionosondes are very well distributed geomagnetically.

The results of Collins, Jelley and Matthews (Reference 6) are an example of the use of this technique. After a suitable comparison with riometer results they set up criteria to diagnose a P.C.A. from ionosonde records. These were:

1. Reasonably continuous blackout conditions, that is, no "non-blackout" for more than 3/4 hour during an event,
2. Duration of blackout greater than 3 hours,
3. Several stations should see blackout conditions simultaneously.

Using information from the Canadian "net" of stations, they found the time distribution of P.C.A. events from 1949 to 1959 (Figure 3) and the distribution of events per month during that time (Figure 4). A satisfactory correlation with the sunspot number is shown, and the tendency for P.C.A.'s to be detected during the northern summer is illustrated.

Statistical examination of P.C.A. events tends to show that the longer the time from solar maximum the greater the effective beam velocity, defined as the distance from the sun to the earth divided by the time between the flare and the start of the P.C.A. event. Another fact to keep in mind is that five out of the six great cosmic ray events have occurred at a time more than two years away from solar maximum.

An examination of the distribution of P.C.A. events in the two hemispheres using this technique shows a definite time correlation between events in the arctic and the antarctic. It has been found that P.C.A. events in the northern hemisphere are associated

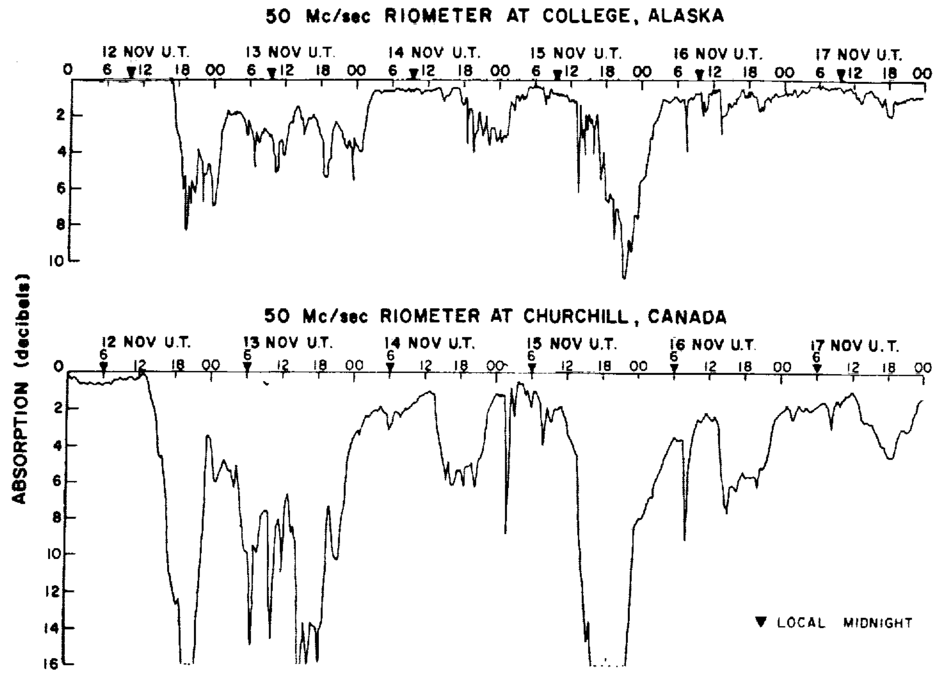

Figure 1 - Riometer records from College, Alaska, and Churchill, Canada, for the November 1960 cosmic ray event (27 Mc/sec)

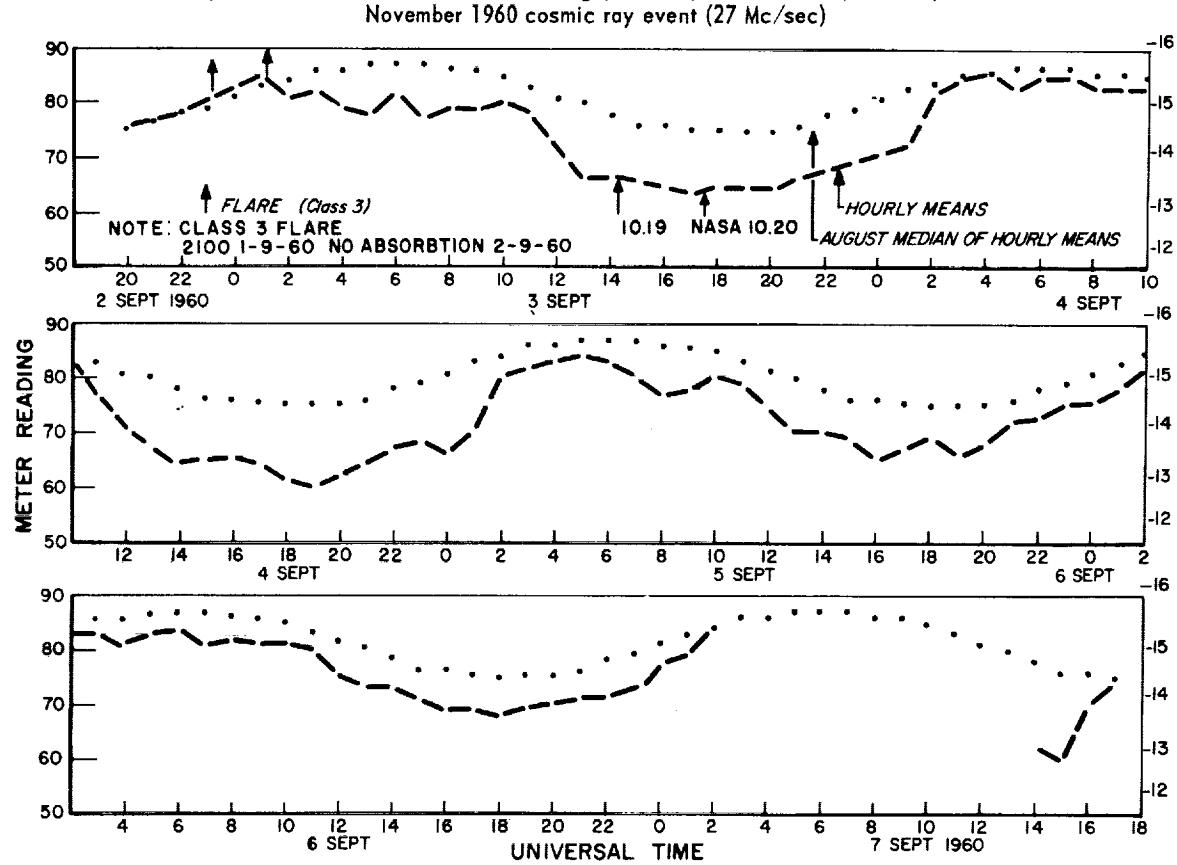

Figure 2 - Churchill, Canada, riometer record during September 1960 (27 Mc/sec)

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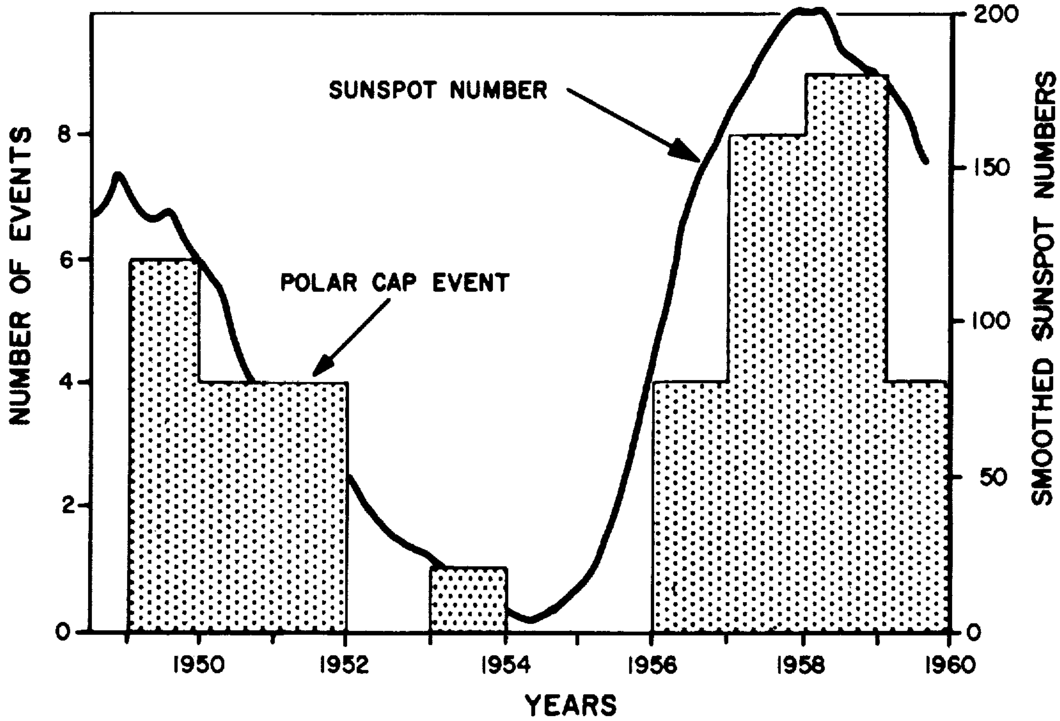

Figure 3 - Distribution of P.C.A. events from 1949 to 1959. From Reference 6.

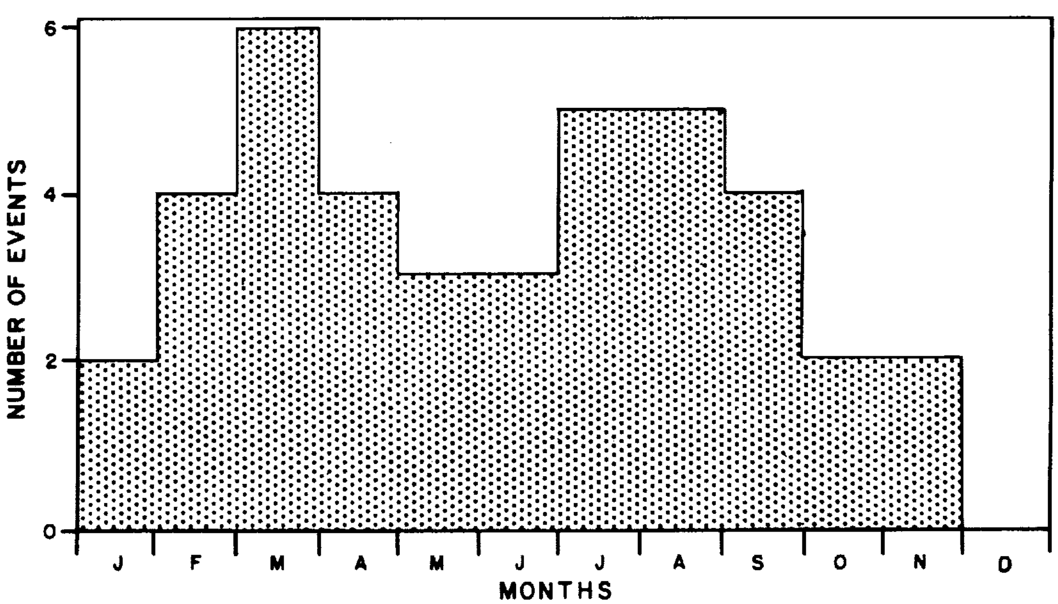

Figure 4 - Distribution of P.C.A. events by month during the period 1949 to 1959.
From Reference 6.

with widespread prolonged ionospheric blackouts in the southern hemisphere, presumably also P.C.A. events. On two occasions (September 26, 1957, and July 29, 1958), out of thirteen studied, no effects could be identified in the antarctic. The northern hemisphere records show low degrees of absorption (2 db and 1 db, respectively) lasting for about 30 hours each time. These results show a number of remarkable features, but only two of which are discussed here:

1. Absorption is frequently found earlier at the geographic pole than at stations of higher magnetic latitude; and
2. P.C.A. events occur during the antarctic summer.

Let us now consider the solar events responsible for these fast particles.

A large chromospheric flare emits a total amount of energy of about 10^{33} ergs. Table 1 gives the approximate division of this energy.

Table 1
Approximate Division of the Energy from a Large Chromospheric Flare

Type	Energy (ergs)
Visible light	10^{30} - 10^{32}
Ultraviolet light	not well known
X rays	10^{28} at 30Å
Radio emission	10^{24} - 10^{26}
Fast particles	
Magnetic storm particles	10^{29} - 10^{30}

The visible light from which the flare takes its name may be so strong that is can be seen directly on the sun's disc. This "white light" emission is thought to be synchrotron radiation from fast electrons. The counterpart of this in the radio region is synchrotron radiations continuum emission over a wide frequency range, which is found to be strongly correlated with the P.C.A. events. Since the intensity of this "type IV" continuum varies rapidly with decreasing frequency, the best way to observe it is to record the centimetric emission over as wide a frequency range as possible. Considering the 31 P.C.A. events between February, 1956, and July, 1959, Kundu and Haddock (Reference 7) have shown that of 28 P.C.A. events which occurred during periods of centimetric observations all 28 were associated with centimetric wave outbursts (Table 2). This table shows that 83 percent of intense board-band centimetric outbursts are associated with P.C.A. events. After a type IV event a center of emission low down in the chromosphere can be formed, lasting for several days. It is also evident that type IV emission detected at both centimetric and at metric wavelengths can occur without P.C.A. events being detected at the earth.*

*Denisse (Reference 8) gives 30 percent as the proportion of 3 and 3+ flares associated with type IV emission.

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Table 2*

Association of Radio Outbursts with Polar Cap Absorption Events (May, 1958-July, 1959)

Radio Outbursts	Centimeter-wave Intensity	Number of Radio Events	Polar Cap Absorption Events		Percentage of Polar Cap Absorption Association
			Yes	No	
Broad-band centimeter-wave outbursts independent of meter-wave outbursts occurrence	Intense and moderate	34	12	2	83
	Intense only	12	10	2	83
Type IV meter-wave outbursts independent of centimeter-wave outbursts occurrence		19	10	9	53
Type IV meter-wave outbursts associated with broad-band centimeter-wave outbursts	Moderate	7	0	7	0
	Intense	12	10	2	83

*From Reference 7

In view of the interest now being taken in shock waves in plasmas, it is interesting that type III bursts, which are considered to be caused by the rapid ejection of particles from the sun with velocities of the order of c/10, are associated with flares. This correlation increases with the magnitude of the flare. If these emissions are shock waves, they may be of interest for the interpretation of other cosmic ray phenomena, for example, Forbush decreases. Type III radio bursts are not correlated with neutron monitor increases, as is shown by the present author and by McLean (private communication).*

In almost every one of the 45 instances since 1956 when there has been a P.C.A. event, a flare on the visible disc of the sun can be considered to be the source. Examinations of these flares in the broadest sense of the term have shown very little that can be used to identify which ones emit particles. The particles are probably accelerated by a Fermi process in the region of high turbulence close to the site of the optical flare. The region

*See also Proceedings of the International Conference on Cosmic Rays and the Earth Storm, Kyoto, Japan, September 1961, *Suppl. J. Phys. Soc. Japan* 17, 1962.

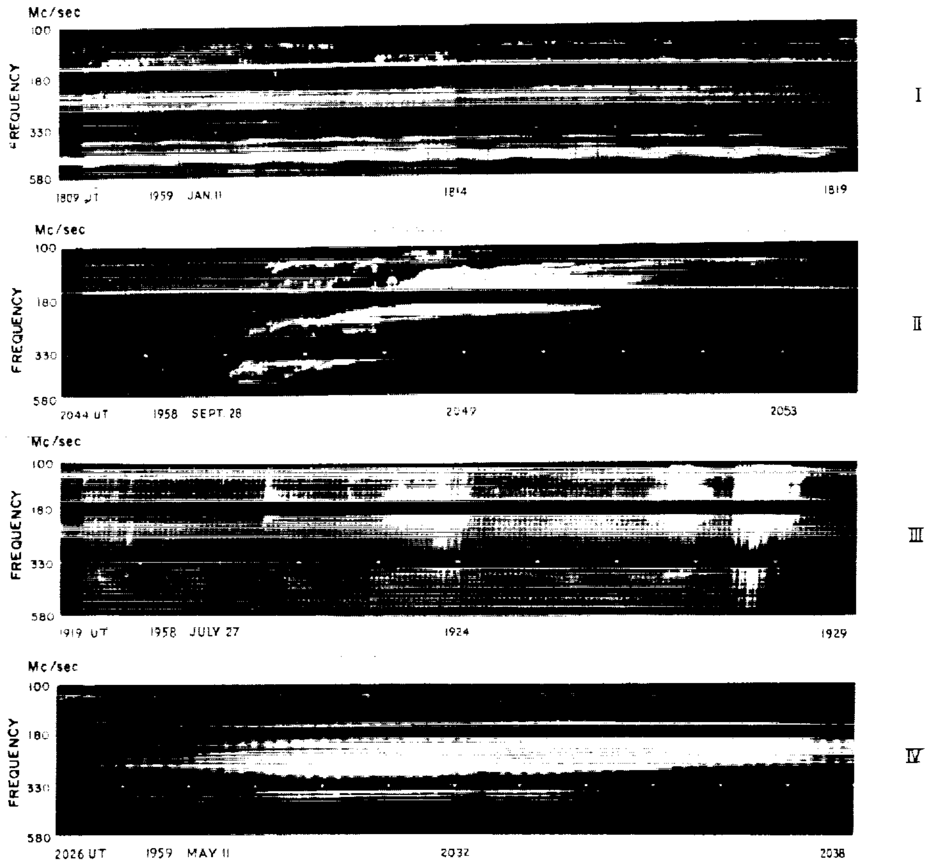

Figure 5 - The four spectral types of solar radio bursts. (I) noise-storm bursts; (II) slow-drift bursts; (III) fast-drift bursts; (IV) continuum bursts. From Swarup, G., Stone, P. H., and Maxwell, A., "The Association of Solar Radio Bursts with Flares and Prominences", The Astrophysical Journal, 131(3):725-738, May 1960

emitting the radio waves can be shown to move away to a considerable distance (of the order of 1 solar radius) with a velocity of the order of 1000 km/sec (Reference 8), and this is consistent with the required lifetime of the particles to provide the correct duration for the radio continuum emissions. Flares which emit particles reaching the earth tend to occur on the western side of the sun's disc, but statistics are poor. A preponderance of events due to flares on the western side might be expected if the particles are thought of as following lines of force drawn out and bent by solar rotation. However, this view is by no means accepted generally. For example, the solid angle into which a solar beam is projected is obviously not small, but nevertheless there are very few events (one or two at the most), which could be attributed to flares taking place beyond the western limb. If there is sometimes a disordered magnetic fields region at a radius of several A. U., as was introduced by Simpson and Parker (Reference 9) to explain the decrease of cosmic ray intensity following the February 23, 1956, event, it does not seem to be a good reflector all the time. Flares near the center of the sun's disc are known to be statistically associated with the largest magnetic storms. Obayashi and Hakura (Reference 10) give the data shown in Table 3.

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Table 3*
Variation of Time Interval Between Flare and Arrival of Protons and Magnetic Storms as a Function of Magnetic Position

Position on Sun's Disc	East 90° - 30°	Center	West 30° - 90°
Average (Protons)	18.3 hr	7.5 hr	3.6 hr
(Magnetic Storm)	37	38	37
ΔH	139 γ	345γ	106 γ

*From Reference 10

As in all statistical studies, due attention should be paid to the criteria of selection in examining the conclusions. This seems especially to be true of solar flare observations, as may be appreciated by referring to Dodson's survey (Reference 11) of solar flares during the International Geophysical Year.

In view of the importance of solar protons to manned space flights it would be very convenient if it were possible to predict when an event would take place. Of course, for long space flights this would not be of much use, the only final method of protection being shielding; but for orbital flights, prediction could possibly be used to save weight. Anderson (Reference 12) has made a study of this problem. He finds that the large flares that produce protons occur in long-lived and complex sunspot groups. The number of sunspots in a group is of no use in prediction, but there does seem to be a correlation between penumbral area in spot groups and the occurrence of flares producing solar protons (Figures 6, 7, 8). This large penumbral area is said to be an unusual feature of spot groups. No attempt has been made by Anderson or anyone else to provide a theoretical basis for this correlation, if it is supposed real.

Because solar proton events last for several days, the commencement of the magnetic storm often occurs during the time that the particles are still coming to the earth. This is a fortunate circumstance because time and latitude variations of the intensity allow us to use the protons to study changes in the field.

The classical geomagnetic storm has a sudden commencement (SC) at which the field H begins to increase. After a period of about one hour, the field undergoes a decrease, lasting for several hours, after which it slowly returns to normal.

In an extensive survey of this subject Bachelet et al. (Reference 13) have found that Forbush decreases are normally associated with magnetic storms of the classical type, or ones in which there is no main phase. Magnetic storms with no sudden commencement, or in which the SC is merely followed by irregular variations, are not associated with Forbush decreases. These magnetic storms not associated with Forbush decreases are typical of solar minimum, and may be correlated with so called M regions, not with typical activity centers. If this is the case, emission of the solar protons from activity centers should be associated with normal magnetic storms, and this is found to be generally correct.

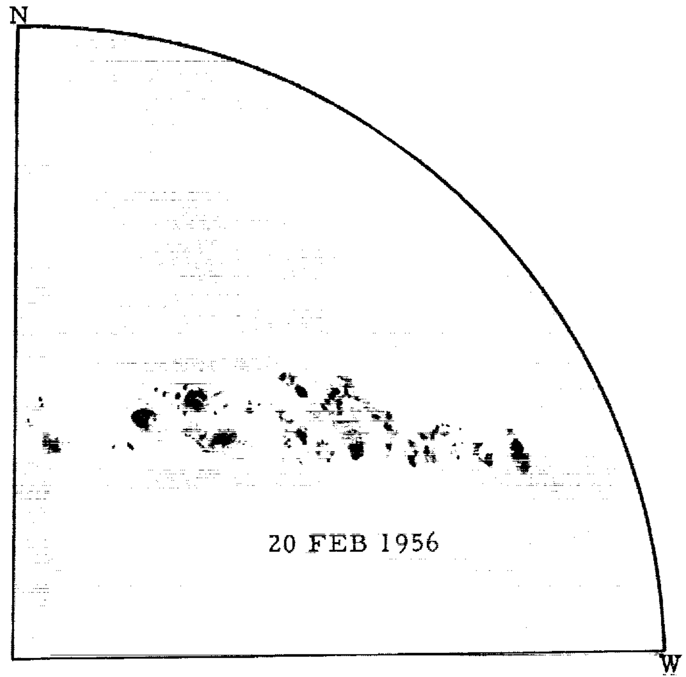

Figure 6 - The sun on February 20, 1956, from a photograph in Publication of the Astronomical Society of the Pacific, 68: 273, 1956. The figure caption states: "The long stream of spots ..... contained five separate groups as indicated by their magnetic fields. The intense flare observed at Tokyo on February 23 was near the center of this stream which was then very close to the west limb." The large penumbral areas are very prominent. From Reference 12.

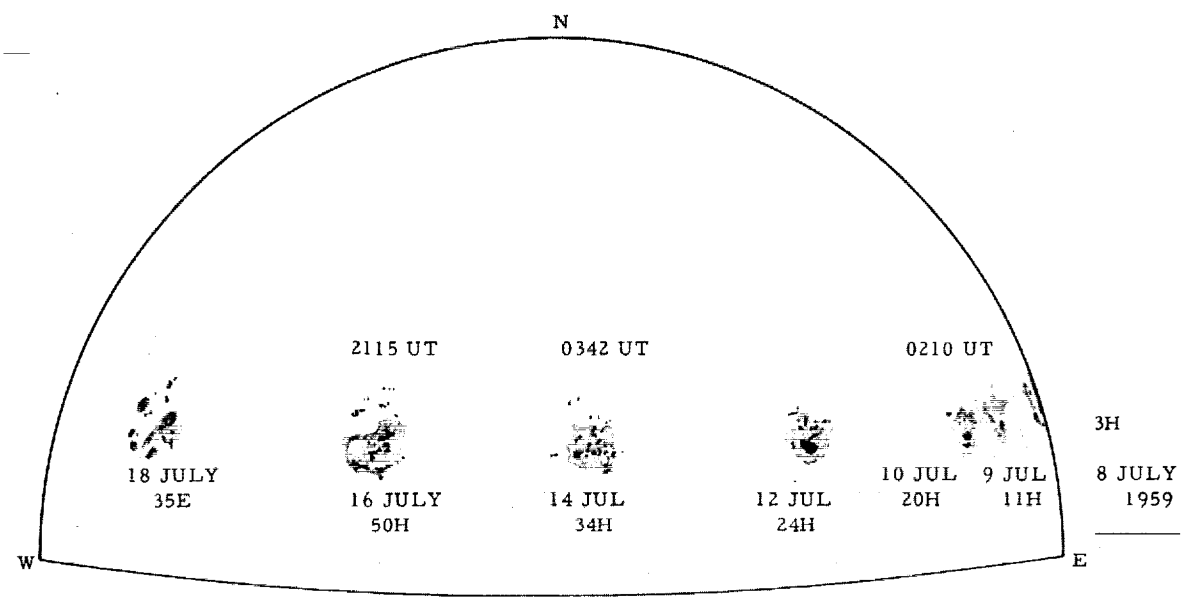

Figure 7 - Two days before the first great July, 1959, solar proton emission, the parent spot group appeared at the limb. It contained only three spots when first seen at Athens, but the penumbral development was already very great. From Reference 12.

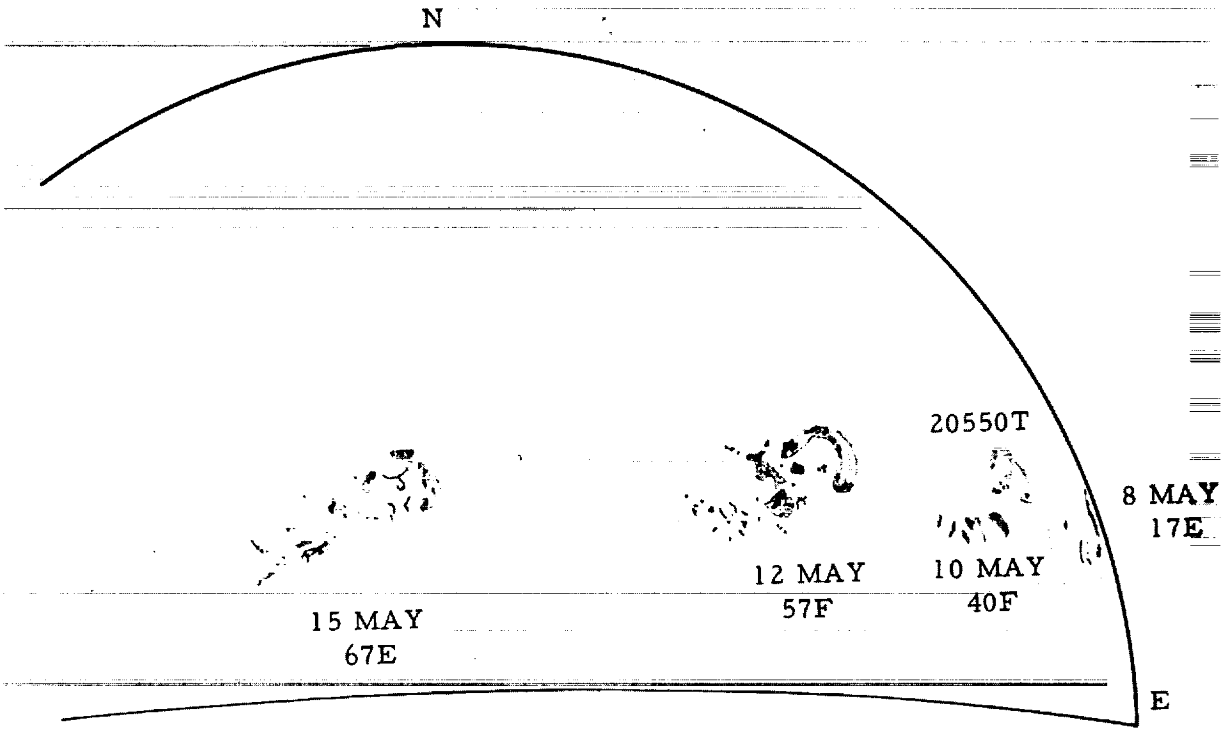

Figure 8 - The flare of May 10, 1959, gave rise to an intense flux of solar protons that reached the earth. Two days before the flare, the large penumbral areas of the sunspot group could be clearly seen, greatly foreshortened, near the east limb. From Reference 12.

The rise in field during the initial phase of the storm is widely held to be due to the compression of the earth's field by an incoming front. Obayashi (Reference 14) has made a calculation on this subject. Noting that the southward edge of the polar blackout moves toward the equator during the main (negative) phase of the storm, they carry through a Stormer calculation using a modified magnetic potential. Instead of simply adding a constant field

$$P = M\left(\frac{1}{R^2} + AR\right) \sin \phi ,$$

where A is a constant and P is the potential, they superimpose the following two conditions successively:

$H_R = 0$ at the boundary of a cavity of radius R_0.

$H = 0$ at the boundary of a cavity of radius R_0.

This gives two potentials

$$P_1 = M\left(\frac{1}{R^2} + \frac{2R}{R_0^3}\right) \sin \phi ,$$

and

$$P_2 = M\left(\frac{1}{R^2} - \frac{R}{R_0^3}\right)\sin\ \phi\ .$$

In the first case (P_1), no line of force crosses the boundary of the cavity $R = R_0$; and in the second (P_2) , the field is drawn out so that the lines of force cross this boundary at right angles. The particles outside the cavity may enter if they have sufficient energy, the distortion of the earth's dipole field by the geomagnetic storm being such as to increase it at the equator during the positive phase, and reduce it during the main phase:

$$H_1 = \frac{2M}{R_0^0}\cos\phi\ ,$$

$$H_2 = -\frac{M}{R_0^3}\cos\phi.$$

The radius of the cavity is thus the parameter which, on this theory, fixes the field change. The first integral of the equations of motion of the proton in a field of this potential is used to find Stormer allowed and forbidden regions. The results of the calculation of the cutoff for vertical incidence as a function of latitude using R_0/R_e as a parameter, are shown in Figures 9 and 10.

This problem is also discussed by Rothwell (Reference 15). In her treatment, the solar gas cloud enters the earth's field and approaches to a distance of several earth radii $(x\ R_e)$ where particles are supposed to leave it and travel along the lines of force of the earth's dipole field. The dipole field is supposed to be unaffected by the cloud at distances less than $R = x\ R_e$. Since there is no "compression" in this model, the cutoffs are only reduced, and the positive part of the storm is not explained. Essentially, the function of the cloud is to bring particles to certain distances and let them start from a point where the potential is higher than at infinity. This idea separates entirely the dynamic and magnetic properties of the cloud, and is thus not very realistic. On the other hand, Obayashis treatment reproduces semi-quantitatively the main features which are actually observed by introducing an a priori assumption. Time will tell whether the type of field which he requires is available in nature, but the compression of the earth's dipole field during the positive phase of the storm does in fact seem to occur.

These matters have been discussed before the main topic because the situation during a solar proton event is very complex. It is essential to bear in mind as many aspects of the geophysical situation as possible, the magnetic field disturbances in particular being essential clues to the processes occurring.

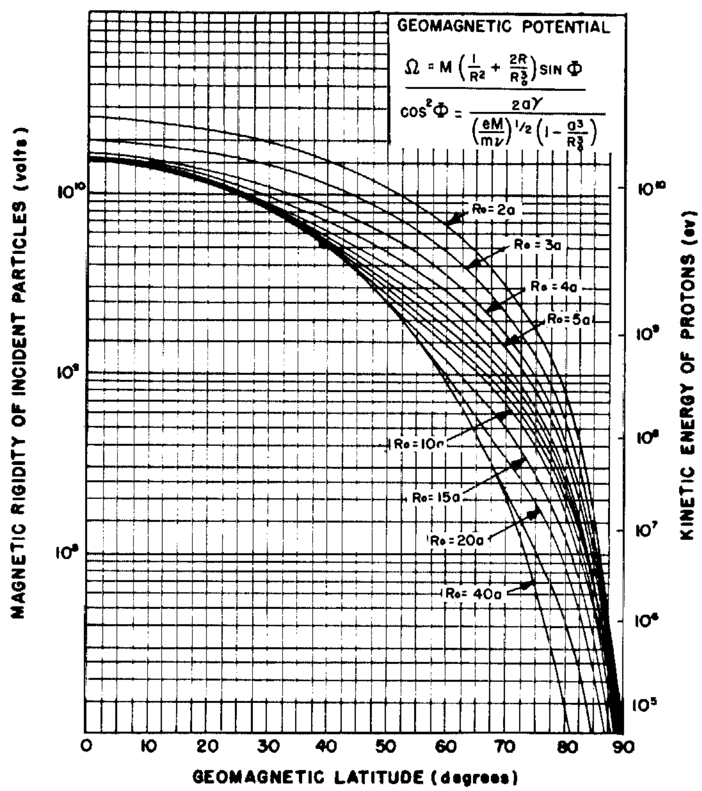

Figure 9 – Geomagentic cutoff rigidity of particles P_1 vs. geomagnetic latitude for various R_0. From Reference 14.

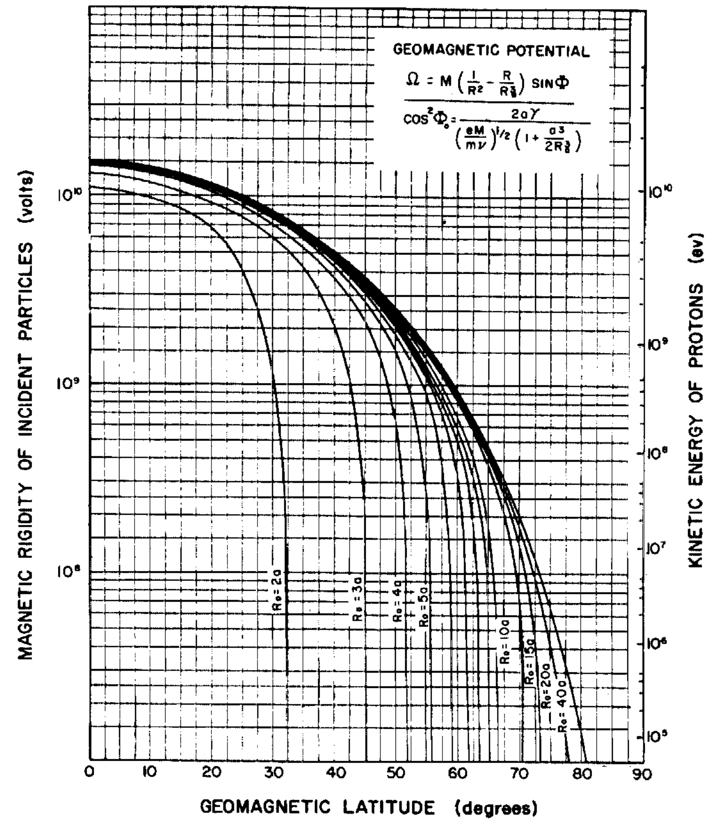

Figure 10 – Geomagnetic cutoff rigidity of particles P_2 vs. geomagnetic latitude for various R_0. From Reference 14.

METHODS OF OBSERVING SOLAR PROTONS

To provide an idea of the relative sensitivities of detectors, some figures calculated by Webber (private communication) are given in Table 4. This very illuminating tabulation shows why the protons incident during P.C.A. events were discovered by the riometer. It is the most sensitive sea level detector of incident charged particles, and this is especially true when there is a steep spectrum. Thus, to get more detailed information about the incident particles—and riometer can, in principle, give a good deal of information about the spectrum and intensity—high altitude observations are essential. The available methods of reaching high altitudes are given in Table 5.

Table 4
Relative Sensitivities of Detectors

Instrument	Altitude and Position	Assumed Minimum Detectability	Increase × C.R. Greater than 100 Mev	
			P^{-6}	P^{-8}*
Ion Chamber	$\lambda = 50°$, S. L.	+2%	10,000	50,000
Neutron Monitor	$\lambda = 60°$, S. L.	+2%	250	1,000
Single Counter	$\lambda = 65°$, 100 gm/cm²	+5%	25	100
Ion Chamber	$\lambda = 65°$, 100 gm/cm²	+5%	15	70
Riometer	$\lambda = 65°$, S. L.	-1/2 db	12	12
Riometer	$\lambda = 67.5°$, S. L.	-1/2 db	2	0.5
Riometer	$\lambda = 70°$, S. L.	-1/2 db	0.2	0.02
Single Counter	$\lambda = 65°$, 10 gm/cm²	+5%	0.2	0.5
Ion Chamber	10 gm/cm²	+5%	0.08	0.2
Satellite or Rocket	2 gm/cm²	+10%	0.01	0.004

*The two columns are obtained by using two spectra for the incident particles, namely power law rigidity spectra with exponents -6 and -8

Table 5
Characteristics of Methods of Observing at High Altitudes

Method	Maximum Altitude (gm/cm²)	Duration	Power
Aircraft	~ 50 gm	~ 10 hrs	large
Rubber balloons	~ 10 gm	up and down	small
Plastic balloons	~ 4 gm	~ 10 hrs	small
Rockets	zero	~ 2 min	small
Satellites	zero	long	small
Space Probes	zero	long	small

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Aircraft were useful when a large power source was often required for complicated experiments, but the use of the transistor and miniature components has eliminated the need for them. Rubber balloons are superseded because they do not float at high altitude, and in fact most of the work being done in this field uses two methods; constant volume plastic balloons and rockets.

It may seem surprising that the rocket, with its inherent limitation of short flight, is of any use compared with the satellite. However, the available satellites are often in orbits which are not inclined at a large angle to the equator. They do not precess in inclination, so the situation is that unless a satellite orbit is inclined at a large angle to the equator, or of great eccentricity such as Explorer XII, it cannot sample the volume of space through which particles approach the polar regions (Figure 11).

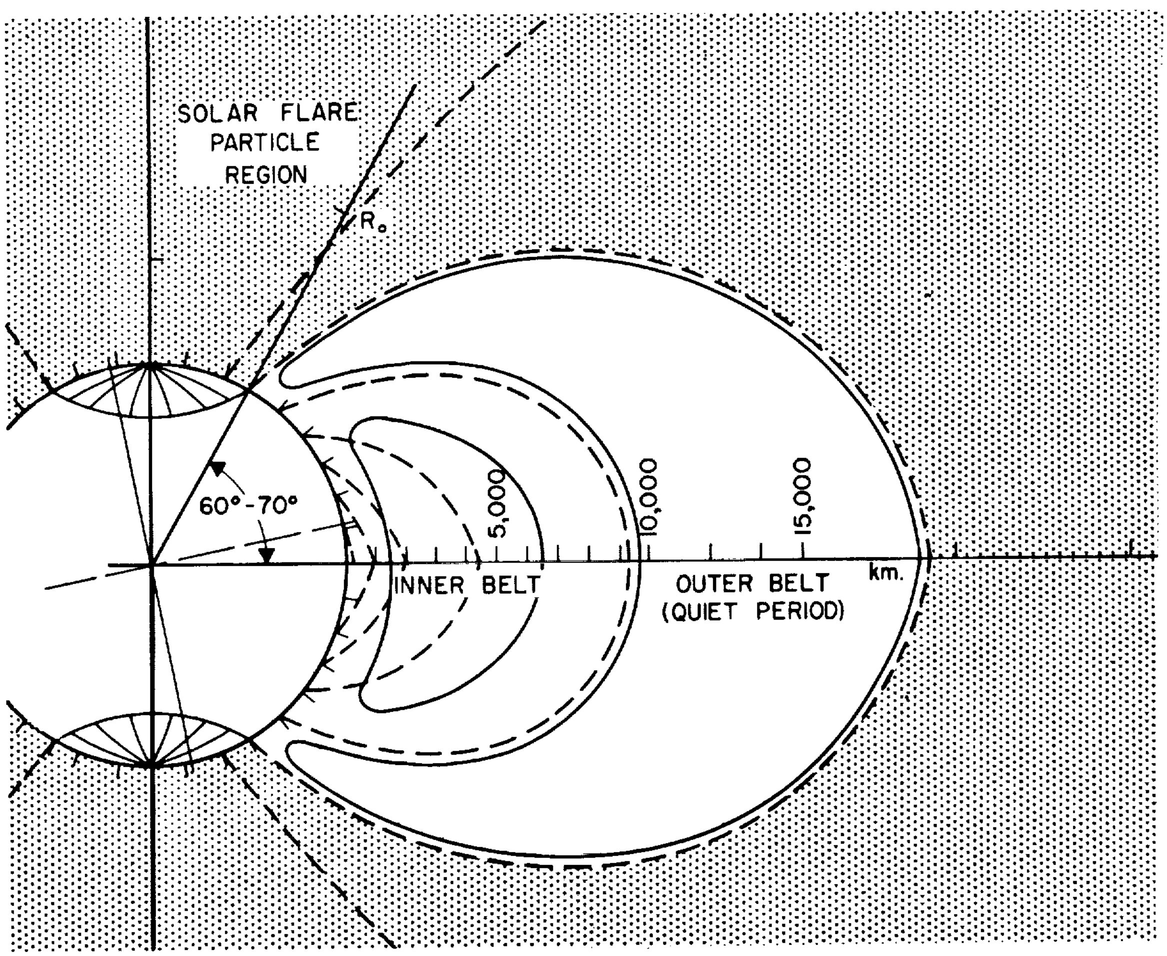

Figure 11 – Geometry of Radiation Belts and Region to which Solar Flare Particles Penetrate

DETECTORS

What should be borne in mind in designing an experiment to detect solar protons? Figure 12 shows the penetration depth of protons in the earth's atmosphere, the corresponding dipole cutoff latitude, and dE/dx. For a rocket experiment, the minimum energy which is to be considered is set by the detector; but for a balloon, the atmospheric cutoff will normally prevent measurements below about 100 Mev. Even an isotropic angular distribution of protons in the upper hemisphere above the atmosphere rapidly becomes peaked at lower altitudes. Thus, at 10 gm/cm², say, most of the protons to be detected will have an ionization of several times minimum and will be travelling vertically. This means that the combination of calibrated ion chambers and a Geiger counter or counter telescope can differentiate between protons and other particles where dE/dx is greater than minimum. This arrangement has been extensively used by Winckler (Reference 16), and by Anderson (Reference 17). See Table 6 and Figure 13.

For example, during the period August 22 to August 25, 1958, balloon flights were carried out at Churchill, Canada, Fairbanks, Alaska, and Minneapolis. The spectrum can be obtained from the plot of the absorption curve of the radiation during the balloon ascent. Anderson et al. (Reference 17) assume:

1. There are only protons present.
2. They are isotropic in the upper hemisphere.
3. They are absorbed by ionization loss alone.
4. There is no scattering.

By introducing a differential energy spectrum of the form $(K/E^{n})\,dE$, and a range-energy relation Range $= E^{u}$; the absorption curve can be calculated as a function of the exponent of the spectrum, and a fit obtained. The result in the particular case was $n = 5$, a

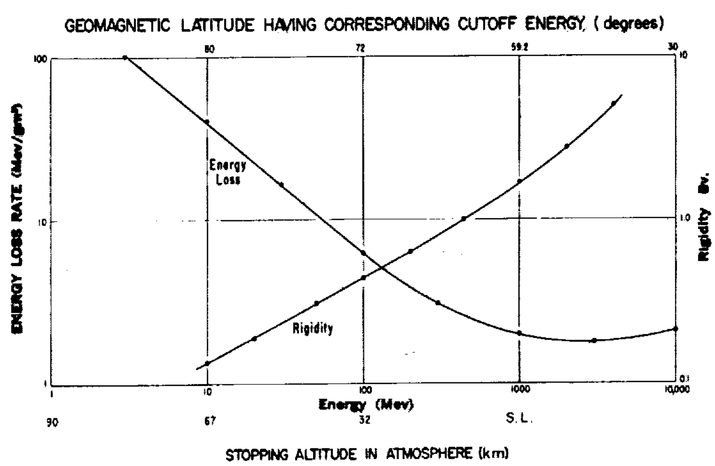

Figure 12 – Energy loss and rigidity as a function of Energy. Depths of penetration into the atmosphere and magnetic coordinates (Querby and Welsko) are shown.

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Table 6
Critical Data on the Monitoring Detector Unit

Detector	Geometry and Dimension	Solid Angle Factor	Wall Thickness and Material	Absorption to the Vertical	Notes
Ion Chamber*	sphere 17.75 cm dia.	Omni-directional projected area 250 cm^2	Aluminum 0.089 cm	0.4 gm/cm^2	Electrometer charge per normalized pulse 0.67×10^{-10} coulombs
Copper counter	cylinder 2.36 cm dia. 1.96 cm effective length	Omni-directional projected area 5.8 cm^2	Copper 0.089 cm	1.5 gm/cm^2	Recovery time 150μ sec Cosmic ray efficiency 94%
Aluminum counter	cylinder 2.36 cm dia 1.96 effective length	Omni-directional projected area 5.8 cm^2	Aluminum 0.051 cm	1 gm/cm^2	Recovery time 150μ sec Cosmic ray efficiency > 94%
Telescope		Solid angle factors 2π omni-directional intensity 5.3 ± 0.5 cm^2-ster 2 cos θ intensity 3.6 ± 0.4 cm^2-ster		1.5 gm/cm^2	Resolving time of coincidence circuit ~ 3μ sec

†From Reference 16.

*Ion pairs/cm^3/sec at NTP air = 12.3×10^3 x ion pulses/sec

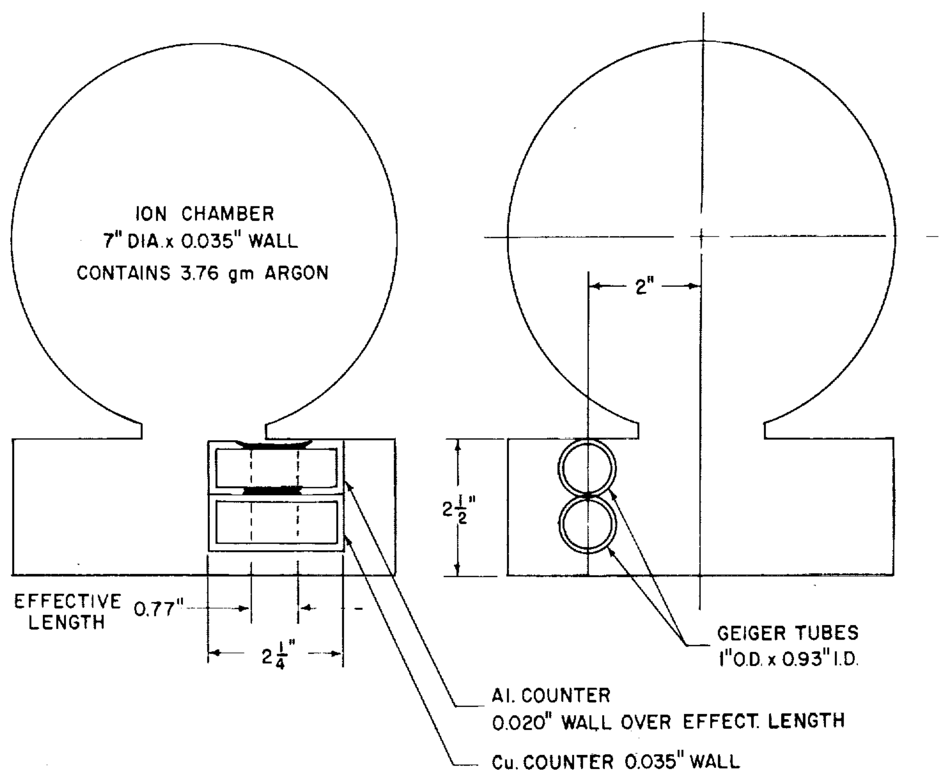

Figure 13 – Geiger Counter and ionization chamber used with balloons by Winkler. From Reference 16.

typical value, and this applied from 250 Mev, corresponding to the depth at which the counting rate started to rise, to about 100 Mev, the air cutoff at high altitude. The agreement of the calculated absorption curve with experiment did not by itself confirm the nature of the radiation as protons, but electrons could not have produced the high value of dE/dx which is inferred from the ratio of the rate of discharge of the ion chamber to the rate of the single counter, about three times that given by normal cosmic rays. This is confirmed by the high degree of directional correlation observed by means of the counter telescope.

Although this method shows that the observations are consistent with a beam of 100 percent protons, it cannot rule out the presence of mixture of high energy electrons and α particles, particularly since adding electrons reduces dE/dx and adding α particles increases it. It would be possible to account for the observations entirely by a mixture of high energy electrons and α particles but this can be shown to be unlikely in a simple way. The transit times would be so different that the ratio observed between the detector rates would vary during the beginning of an event, which is not observed.

A good confirmation of the nature of the particles is provided by simultaneous observations at different points. As an example of this technique consider the same event, as shown in Figure 14. The flights at Churchill, Minneapolis, and Fairbanks focus attention on the following points.

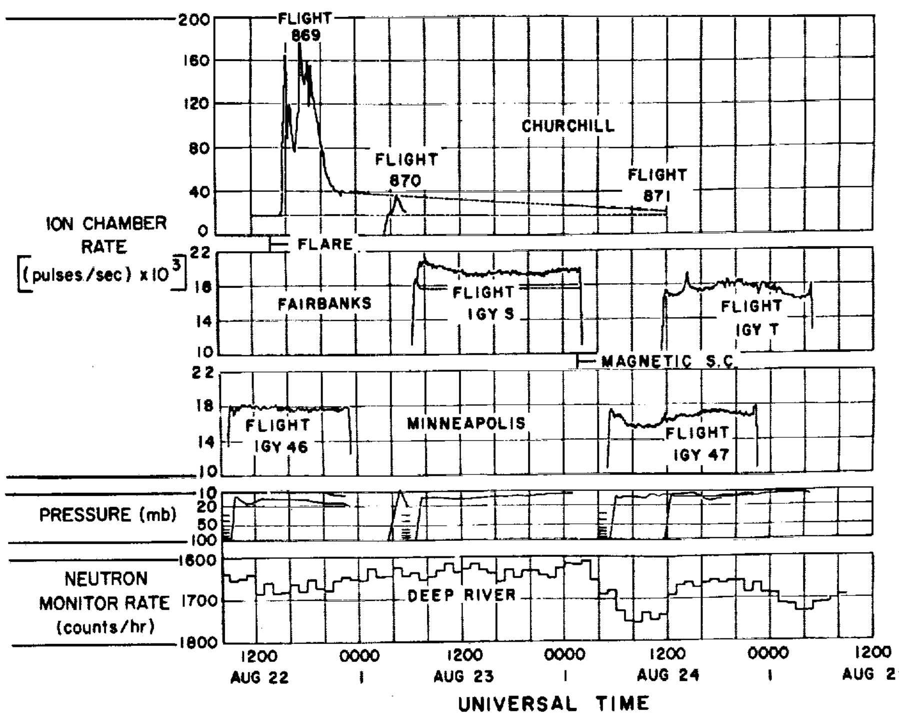

Figure 14 – Balloon observations and correlated data during the cosmic-ray event of August 22, 1958. Top line, observations at Churchill; next lower, observations at Fairbanks; center, observations at Minneapolis; next lower, balloon pressure curve; and bottom, Deep River sea-level neutron monitor. From Reference 15.

1. The long period of observation at constant altitude provided by a successful flight.
2. The absence of an increase at Minneapolis.
3. The Forbush decrease observed at high altitude.

The absence of the increase at Minneapolis shows that there were no protons incident there with enough energy to overcome the cutoff. In addition, this also puts an upper limit to the abundance of radiations not subject to a cutoff, namely neutrons and photons. For this particular event these limits were 12 percent with energy greater than 40 Mev and 10 percent with energy greater than 500 kev, respectively. Again the event seems to be typical, because subsequent measurements have confirmed that the composition of the beam is always principally protons.

Observations at high altitude and medium latitudes—for example, those at Minneapolis—have a great additional bonus. If particles do appear there, and are identified as protons, then this becomes evidence of a cutoff change (Figure 15 and 16). In the event of August 22, 1958, there was no geomagnetic storm. This is entirely consistent with the idea that

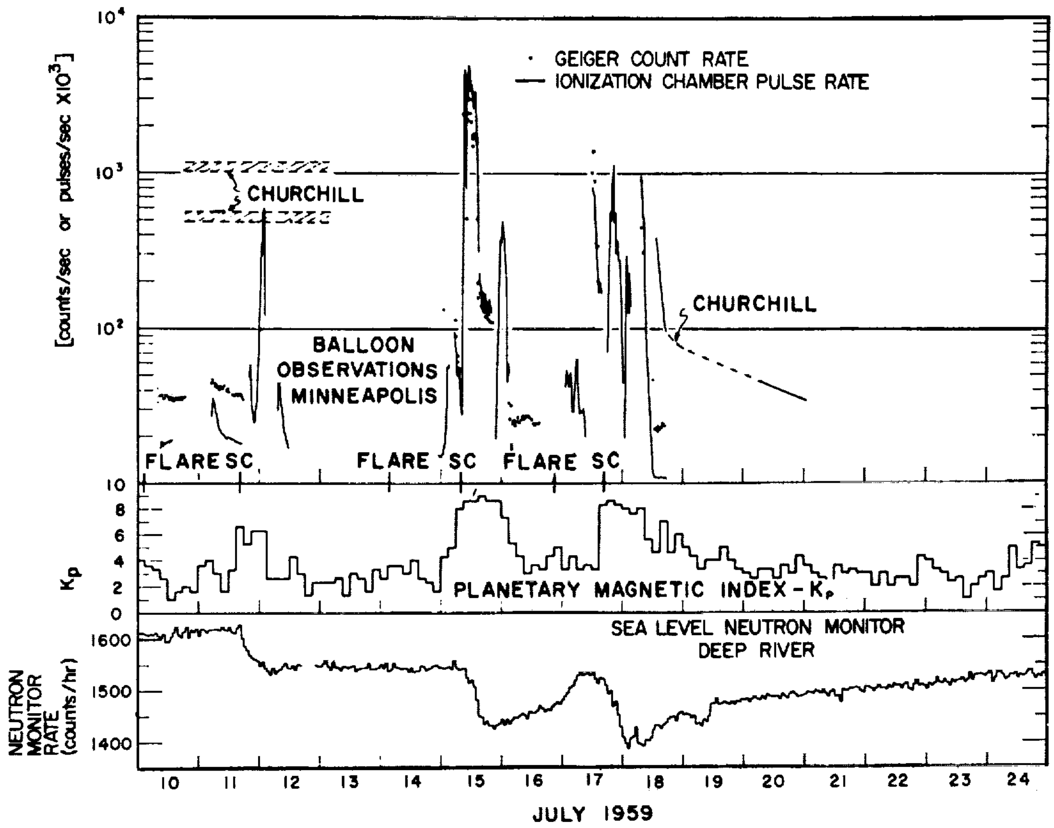

Figure 15 - Upper: High-altitude total ionization (solid curve) and counter rate (dotted curve) during the three July events. Note logarithmic scale. Center: Note general correlation between influx of radiation and planetary K indices. Lower: Sea-level neutron intensity showing the three large Forbush decreases strongly correlated with the magnetic activity. On July 17, the flare cosmic ray produced a sea-level effect before the geomagnetic disturbance that is attributed to the energy spectrum extending appreciably into the high-energy range of at least 1 Bev. From Reference 16.

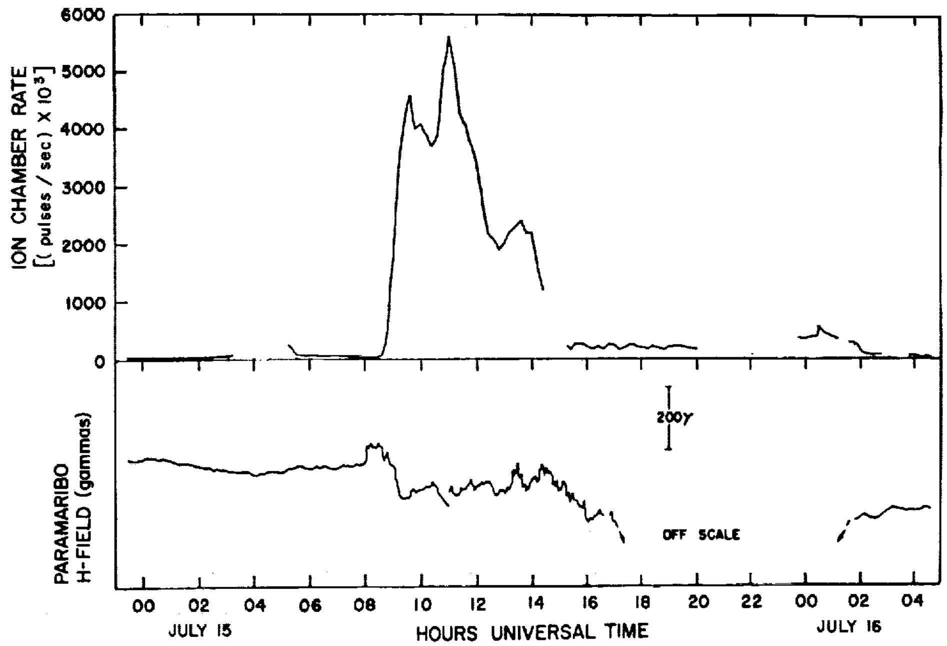

Figure 16 - High-altitude ionization rate, above, and equatorial horizontal field of the earth below, during the second geomagnetic storm of the July series. Note that the major increase at Minneapolis occurred when the storm field entered the main phase, in this case only about 1/2 hour after the sudden commencement. From Reference 16.

the cutoffs are lowered during the main phase of a geomagnetic storm. When this occurs, auroral X rays may be observed at balloon altitude. If the balloon is within a few hundred kilometers of a riometer, simultaneous characteristic auroral absorption can often be identified on the riometer record. The energy of the X rays is in the range of 50 to 100 kev. The electrons required to produce the X rays are either contained in the plasma cloud which is thought to distort the field by compression, or they are locally accelerated, or they are dumped from the Van Allen belt. All three possibilities are reasonable, and any or all may occur.

A theoretical treatment of the generation of X rays by electrons coming into the earth's atmosphere has recently been given by Cladis and Dessler (Reference 18). The subject of auroral X rays is an interesting one but it is not considered here (see Reference 19).

If recovery can be arranged, nuclear emulsions are a good help in the experimental study of solar protons. Although they give no indication of time variations, they allow the identification of small numbers of α's and heavy nuclei in the flux in a way which is very hard to achieve by any other method. This approach has been exploited by Freier (Reference 20) and Fichtel (Reference 21). Freier has used emulsions to study the composition of the incident particles in the manner indicated above, and also to measure the cutoff at Minneapolis as a function of time during the magnetic storm, using emulsions exposed during several flights into the same event.

On March 23, 1958, at 0950 U.T., a class 3+ solar flare was observed with a duration of 248 minutes. A type IV radio noise storm was observed 169 to 9400 Mc) and this storm was extremely large at low frequencies. There was a sudden commencement and a Forbush decrease starting late on the 25th, and about this time a P.C.A. event with 10 db of absorption started at Fort Yukon, Canada. Balloon flights were made into this event from Minneapolis on March 21, March 26, and April 8, each carrying a single counter, an ion chamber, and nuclear emulsions. The ion chamber gave a very clear record of the Forbush decrease at high altitude, agreeing well with the Deep River, Canada, neutron monitor. The increase of ionization which indicates the arrival of the low energy protons was observed directly. The emulsions showed that a large increase in the proton intensity was not accompanied by a corresponding increase in the intensity of α particles at rigidities greater than 1.3 Bv (approximately 200 Mev/nucleon). This puts the proportion α/p above a given rigidity at less than the α/p ratio which is characteristic of galactic cosmic radiation (1/18 in this event). Freier, Biswas and Stein (Reference 20) have measured the α/p ratio in the rigidity region 0.9 to 1.3 Bv, on September 3, 1960, and find that it is $1/(31 \pm 8)$, characteristic of the sun rather than galactic cosmic rays. The final answer to the question of the composition of the beam is not known, but it can be said that the proportion of α particles is appreciable and probably variable; their spectrum must, however, wait until the analysis of the November 12, 1960, event is complete.

Fichtel has studied the proportion of heavy nuclei in the September 3, 1960, solar beam, using the NASA rocket 1019, which was flown at 1408 U.T. (13 hours after the flare). By comparison with nuclear emulsions flown during a test shot at a "quiet" time, he finds that the medium-to-proton ratio above a given rigidity is consistent with the solar constitution as estimated by Goldberg (Reference 22) and differing from the galactic cosmic ray value by several standard deviations. Statistics were too poor to permit deduction of a spectrum (Tables 7 and 8).

The Minnesota group has used emulsions to supply additional evidence of the cutoff changes. They estimate in this way that the normal cutoff at Minneapolis is about 280 Mev, and show how this is altered by a magnetic storm (Figures 15 and 16).

Table 7

Ratio of Nuclei with $6 \le Z \le 8$ to those with $Z = 1$ in Solar Beams

Charge	Ratio
September 3, 1960, SBE	$(0.8 \pm 0.3) \times 10^{-3}$
November 12, 1960, SBE	$(1.9 \pm 0.6) \times 10^{-3}$
Sun	$(1.5 \pm 0.5) \times 10^{-3}$
Universe	$(1.6 \pm 0.8) \times 10^{-3}$
Cosmic Rays	$(10 \pm 2) \times 10^{-3}$

Table 8

Relative Abundances of Nuclei in Solar Beams

Charge	3 to 5	6	7	8	10	Z > 10
September 3, 1960, SBE	0	10	4 ≤	11	5	2
November 12, 1960, SBE	0	13	6 ≤	23	3	1
Sun	10^{-5}	10	2	18	?	2
Cosmic Rays	6	10	5 ≤	6	2	5

Apart from the authors already mentioned, R.R. Brown has made many flights from College, Alaska, which give result in general agreement with those discussed here. Also, the Russians (Reference 23) have made a number of balloon flights at various latitudes.

ROCKET OBSERVATIONS DURING SEPTEMBER AND NOVEMBER, 1960

We shall now turn to the rocket observations of solar protons carried out at Churchill by Davis et al. (References 24, 25, 26). These rockets were Nike-Cajun two-stage types and reach a peak altitude of 130 km, spending about 200 seconds above 90 km. In an attempt to cover as wide an energy and intensity range as possible, a rather complicated system was used. Two scintillation counters and a Geiger counter were carried by the rocket, each telemetering information through a ratemeter. The ratemeter output was arranged to show pulses on the record when the rate was low, and give a voltage output for high rates. In this way, counting rates ranging from a few per second up to 20,000 per second were successfully recorded. Four events were encountered during a continuous watch lasting from June 6, 1960, to the end of the November 12, 1960 event. Arrangements were made with the personnel of the McMath-Hulbert Observatory, the Sacramento Peak Observatory, the Lockheed Observatory, and the University of Hawaii for them to telephone Churchill when a suitable flare was seen. The riometer stations at College, Kiruna, and Churchill were also available by telephone. The rocket instruments were kept in readiness and the rocket was on the launcher at all times. The first event which was detected was on September 3, 1960. The delay between the flare and the start of absorption occurring at 0040 U.T. was about 10 hours, very much longer than usual. The riometer record shown in Figure 17 and Figure 1 gives these results to a larger scale, showing the times of the rocket firings, and the diurnal effect. The diagnosing of the rather small absorption during the early part of September 3 was helped by the presence in Churchill of a team from Dr. Winckler's group who were launching balloons. They had a balloon up, and their telescope rate was sufficiently high (25 times normal) to decide the issue. In table 9, taken from Reference 27, the solar-terrestrial events during the period of interest are shown.

It is assumed that the third flare is the one of interest. During the early part of the previous night at Churchill, there was an extensive and impressive auroral display,

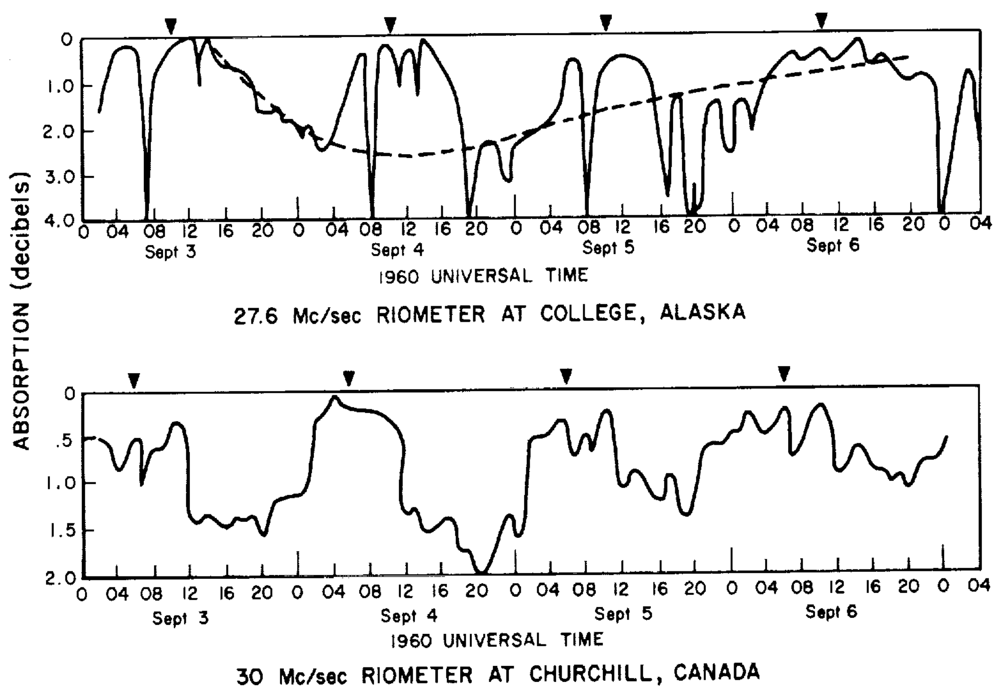

Figure 17 - Polar Cap Absorption event of September 3, 1960

Table 9*

Solar-Terrestrial Time Table

Time (U.T.) Date	Event	Comment on Tentative Identification
0700, Sept. 2	Class 3 flare	Solar coordinates 19°N, 25°W; Source of magnetic cloud, SC and Forbush decrease.
2230, Sept. 2	Class 3 flare	Solar coordinates 21°N, 31°W; Source of apparent non-magnetic cloud but strong magnetic storm.
0040, Sept. 3	Class 3 flare	Solar coordinates 17°N, 90°E; Source of cosmic rays.
0116, Sept. 3	Class 3 flare	Cosmic ray flare maximum, X ray burst (local).
0230, Sept. 4	SC	Begin magnetic storm from 0700 flare Sept. 2
0230, Sept. 4	Forbush decrease	Indicates magnetic character of solar cloud.
1830, Sept. 4	SC	Begin magnetic storm from 2230 flare Sept. 2. No Forbush effect.

*From Reference 27

presumably from an earlier flare. Figure 18 shows that the radiation did not reach its maximum intensity until about nine hours after the flare. The dotted curve 7a represents the spectrum deduced from the emulsions on flight 1019, and curve 8 represents the results from the Geiger counters on flight 1020. The Geiger counter results from flight 1019 agree well with the emulsions but are not shown here to avoid confusion. We note that the spectrum of protons curved away from a power law at low energies, but that in the region of 100 Mev agreement between balloon and rocket observations is good. Also, the intensity was the same at the time of both firings, and it was probably essentially constant for most of the time between. The spectrum steepens with time during both the increase and the decrease of the intensity. The energy spectrum observed is a result of dispersion operating on the original spectrum, which must be assumed to be injected by the sun during a period of time of the order of one hour, the duration of the radio event. Winckler (Reference 27) has suggested diffusion with an energy-dependent mean free path, to account for this, consistent with the prompt arrival of particles on February 23, 1956, for example. In passing, it is interesting to note that very low energy particles were seen over Minneapolis, the instrumental limit being air absorption, on September 4 after the main phase of the geomagnetic storm began.

*Because of a malfunction, the results obtained from the scintillators on September 3 are not presented here.

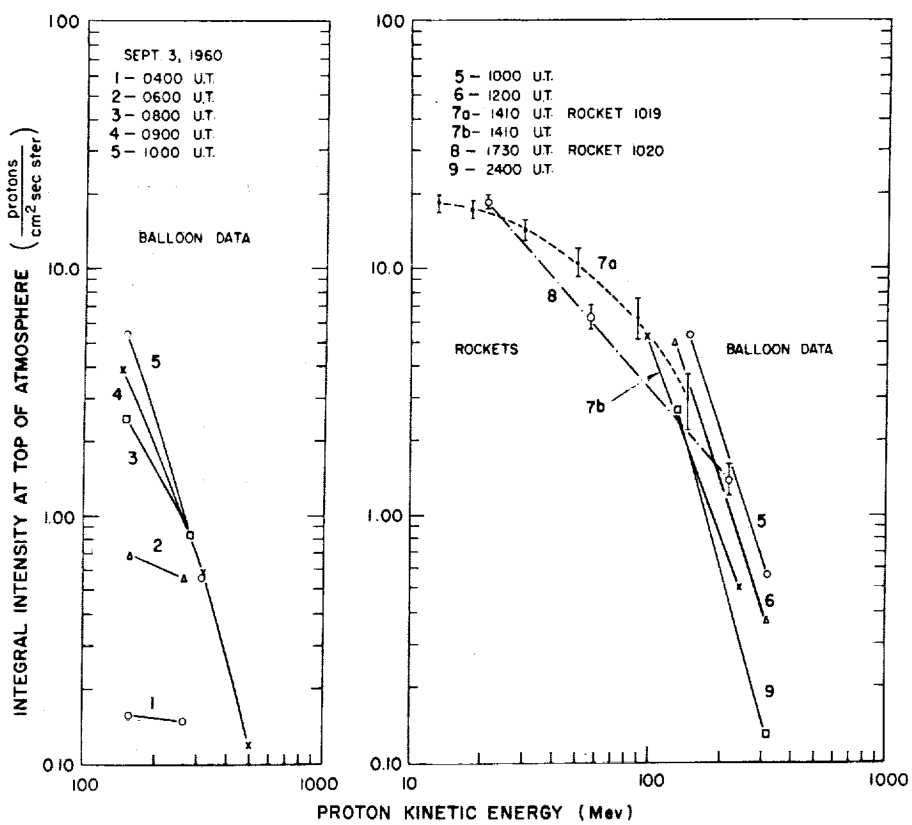

Figure 18 - Balloon and Rocket observations during September 3, 1960 solar proton event, Churchill

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From the September 3 event, the conclusion is that particles with energies down to 13 Mev were detected, that they were protons, and that their distribution in angle above the atmosphere was closely isotropic. It should be pointed out here that D'Arcy (Reference 28) has drawn attention to a possible error of interpretation of balloon flight results. The X rays produced by nuclear reactions in the atmosphere may lead to a larger counting rate than is characteristic of the primary protons. This error could occur in the Geiger counter results given here due to reactions in the (Al) walls of the rocket. However, the agreement between the emulsion and Geiger counter points shows that this effect is small.

The solar proton event of November, 1960, was one of the largest yet observed—perhaps it will be the largest in this solar cycle—and NASA was fortunate enough to fire seven rockets at various times during the period of high proton intensity. Analysis of the results from the first three of these, two fired on November 12 and one on November 13, is fairly complete, and the results will be discussed here. For this event we have scintillation counter records that are self-consistent and show the presence of particles with energies down to 2 Mev. After further analysis we shall have information at much lower energies. Figure 19 shows the times of these first three shots, superimposed upon the neutron monitor record from the Chicago station (Simpson, private communication). The timing of the first two shots was, to say the least, lucky.

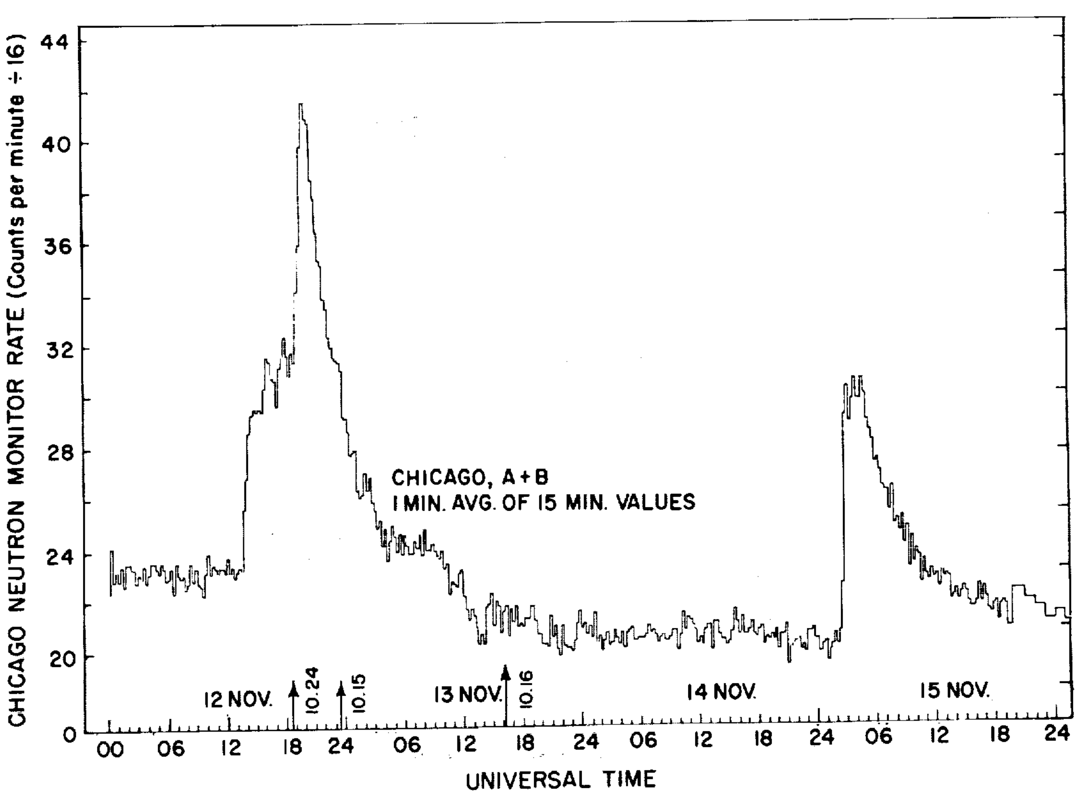

Figure 19 - Neutron monitor record from Chicago for November 12 - 16, 1960

It is necessary now to discuss the method of analysis of the Scintillator results, so that their significance can be appreciated. The two scintillation counters carried by the rockets were fitted with a 0.24 gm/cm^2 CsI crystal in one case, and a ZnS power phosphor in the other. The ZnS results have not yet been reduced but they will eventually give information down to 200 kev. The CsI scintillation counter incorporates a rotating switch which continually changes the load of the photomultiplier. The energy loss vs. energy curve for the crystal is shown in Figure 20. Each load resistor corresponds to a different horizontal line on this diagram, the equivalent energy loss begin exceded by protons in a certain energy range. In particular step 1, the uppermost step, would not count at all if it were not for the fact that some protons enter the crystal at oblique angles, outside the proscribed solid angle, and lose more than the 8 Mev characteristic of perpendicular penetration. We have used in this analysis, the ratios between the step rates 4/5, 3/5, 1/5. We start by calculating these ratios assuming protons incident isotropically upon the detector and rocket, and having a power law spectrum $N(>E) = A/E^n$. This calculation was made for a series of values of n, and the results for the first rocket, NASA 1024 rocket are shown in Figure 21. The observed ratios are seen superimposed, indicating a best fit for a value of $n = 1.6 \pm 0.1$. The intensity of protons having energies above 2 Mev can be obtained from the rate on the "widest" step, (step 5) once a slope for the best power law approximation has been determined.

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Thus, in each case the results from the CsI scintillation counter determine the intensity above 2 Mev and the slope of the best straight line approximation to the spectrum

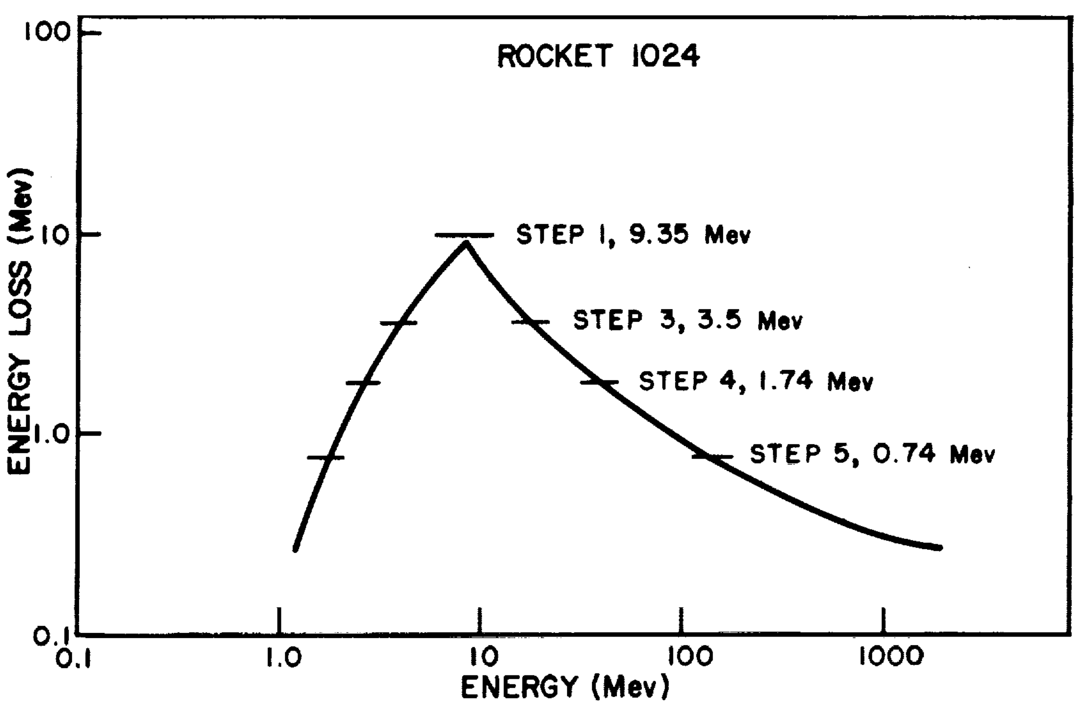

Figure 20 - Energy sensitivity intervals for CsI scintillation counter

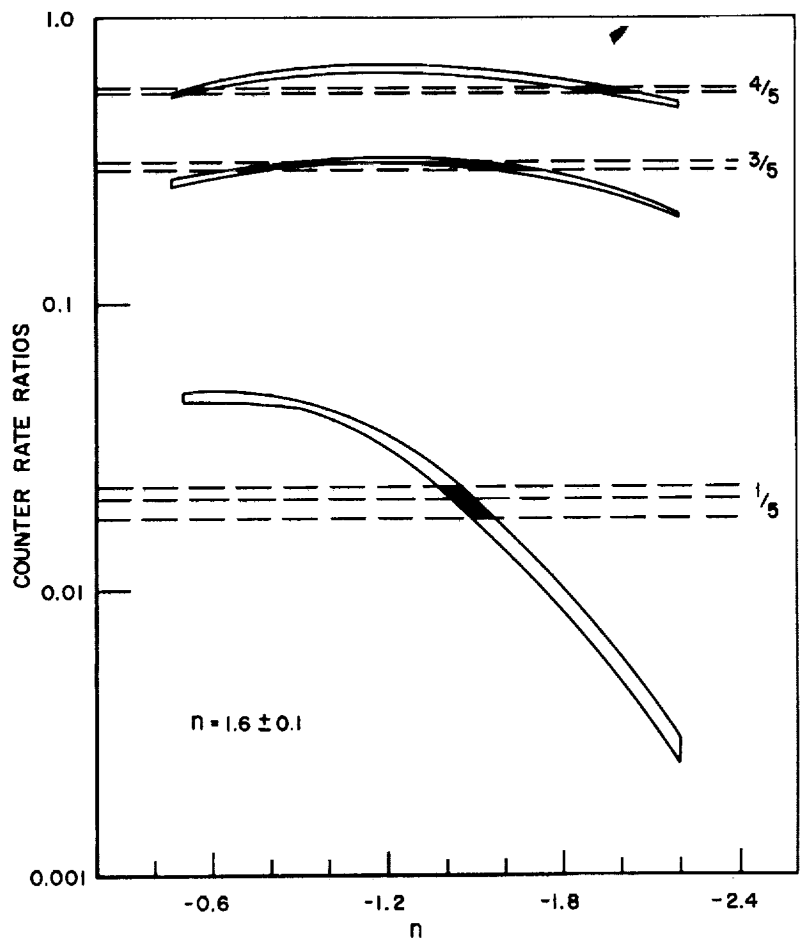

Figure 21 - Ratio calculation results for NASA rocket 1024

between there and about 100 Mev (Figure 22). We do not believe firmly in the existence of a simple power law spectrum in this region, but this approximation can be used until more definite evidence is available. In particular, the emulsion results presented by Fichtel (Reference 29) indicate appreciable flattening of the spectrum in the region between 100 and 15 Mev. This should not be thought to be contradictory to the results presented here. If a spectrum deduced by some other means becomes available, it will not be difficult to test the degree to which it is compatible with these results.

As examples of this procedure Figures 22, 23, and 24 show the actual results of rockets 1024, 1015, and 1016. The inset shows the timing of these shots compared with the neutron monitor increase observed at Deep River. Evidence that the protons arrive isotropically in the upper hemisphere at the top of the atmosphere is provided by the angular distributions shown in Figures 25 and 26.

If the ratio 4/5 is closely equal to the ratio 3/5, this indicates both a steep spectrum, and an absence of low energy particles. This situation occurs with Rocket 1016 (Figure 27),

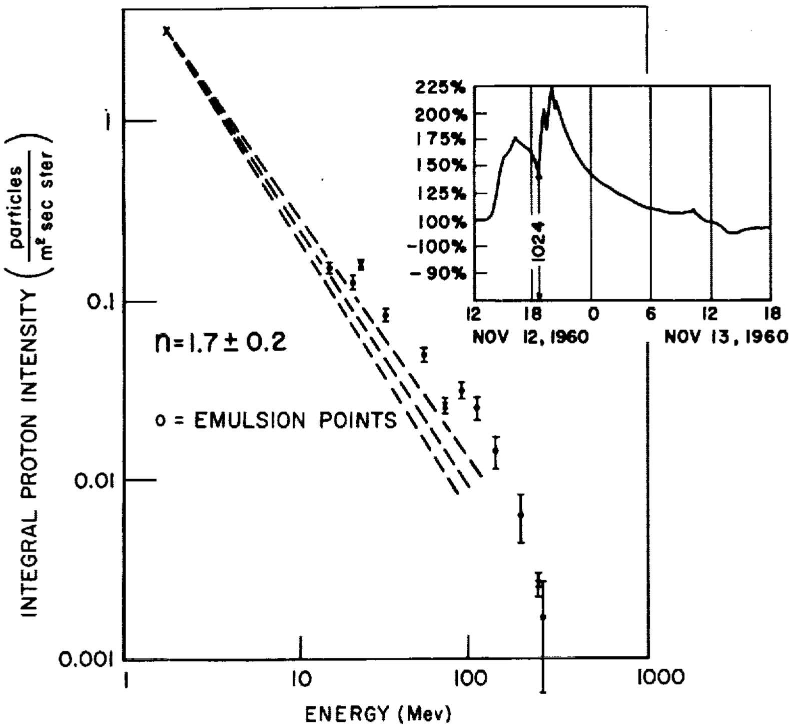

Figure 22 – Spectrum of protons obtained by NASA rocket 1024

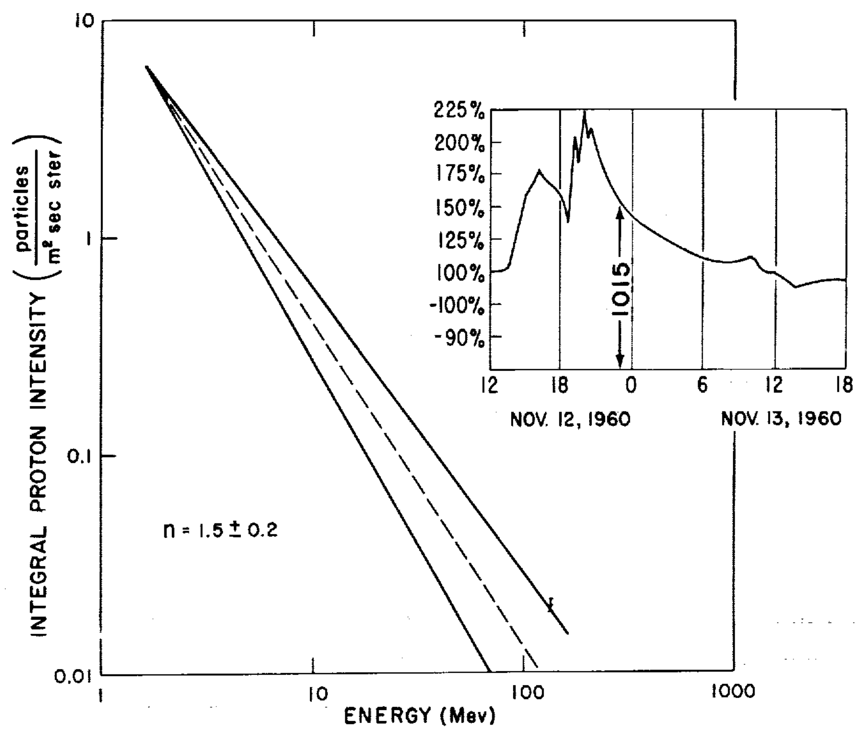

Figure 23 - Spectrum of protons obtained by NASA rocket 1015

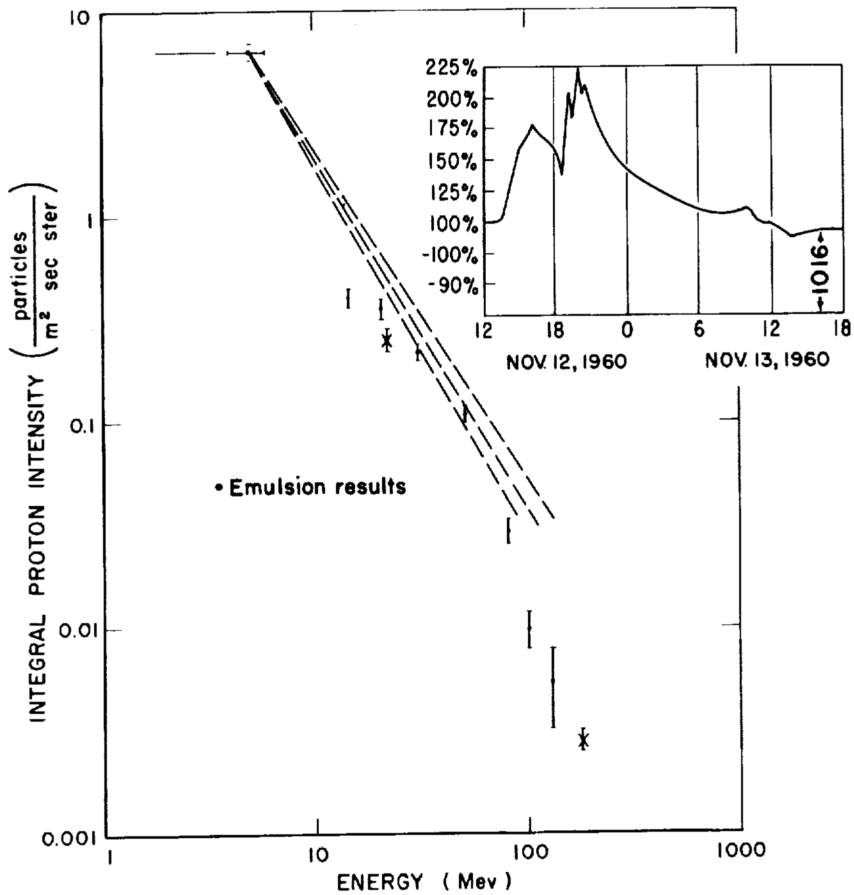

Figure 24 – Spectrum of protons obtained by NASA rocket 1016

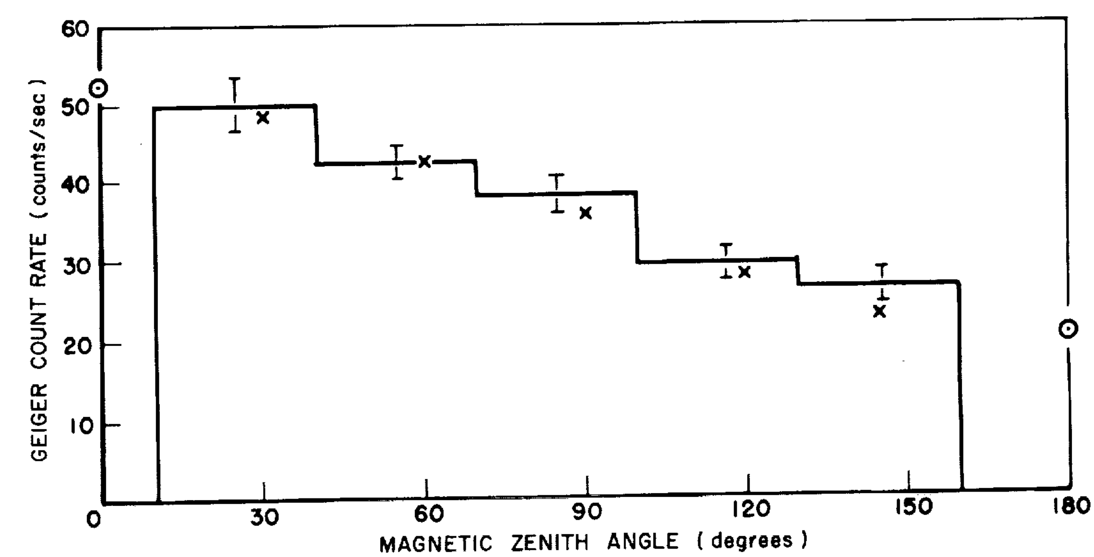

Figure 25—Geiger counter zenith angle dependence-points X calculated assuming isotrophy NASA rocket 1020

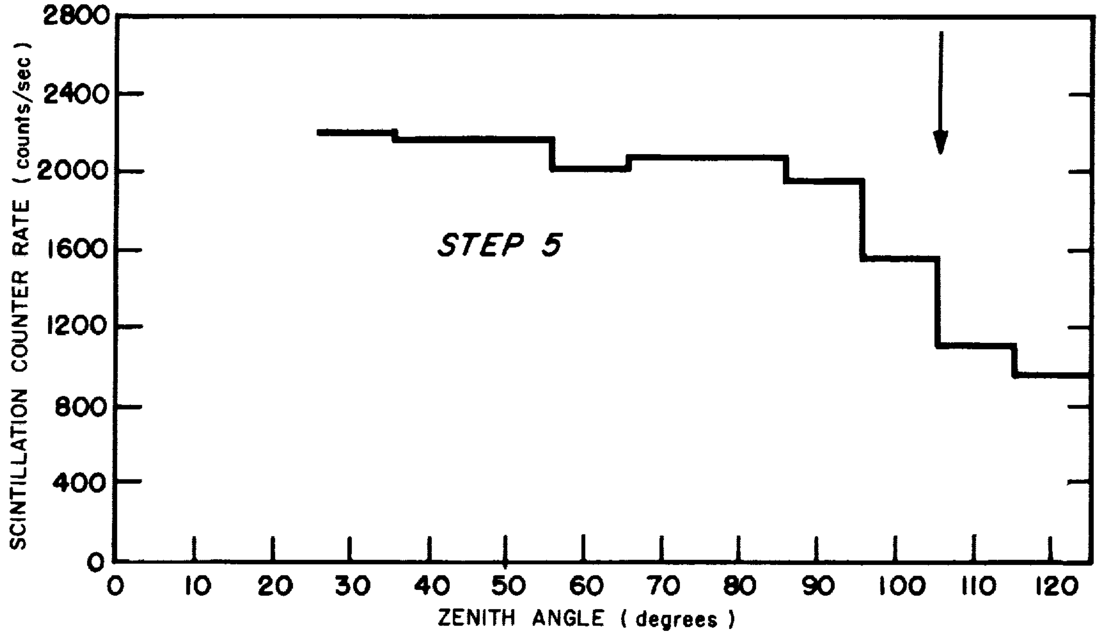

Figure 26 - Angular distribution of protons with energies above 2 Mev, from the CsI scintillation counter in NASA rocket 1024

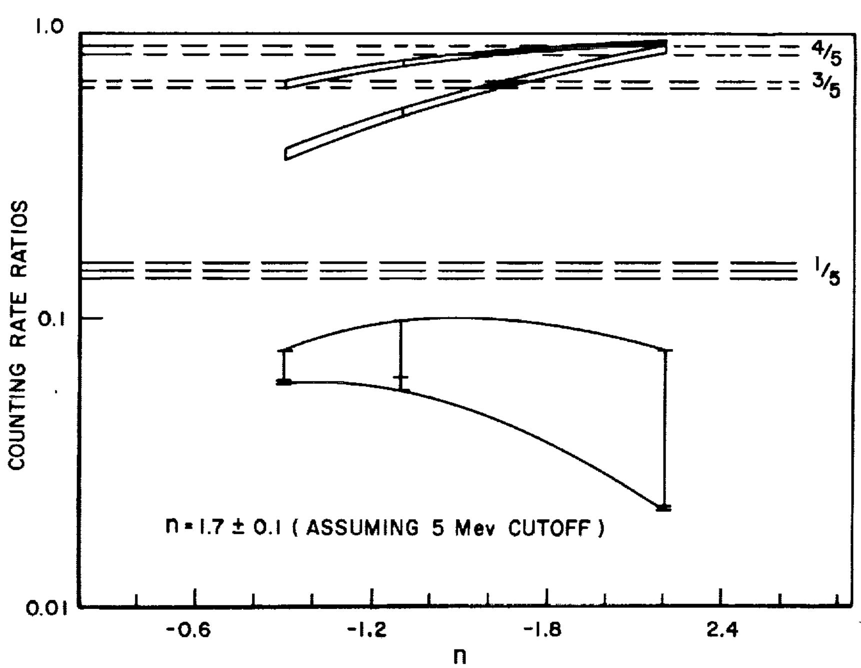

Figure 27 - Ratio calculations results for NASA rocket 1016

and this is dealt with by cutting off the spectrum at a low energy and making a two-parameter fit. It was found that the best results are obtained by assuming no particles with energies below 5 ± 1 Mev. Thus, to the degree of accuracy of our experiment, the proton spectrum can be represented by a power law, with or without a cutoff above 2 Mev, and an intensity value either at 2 Mev or at the cutoff energy, deduced from the rate of step 5. Since the analysis of this event is as yet very incomplete, no interpretation will be presented here. However, some remarks can be made. First of all, the neutron monitor increase represents the way in which the intensity of particles at energies about 1 Bev behaved in time. There is a fairly rapid increase, a "step", and a further increase followed by a slower decay. This "step" feature will be discussed later. The intensity of protons at low energies (3 Mev) had the values shown in Table 10. This table illustrates the steepening of the spectrum, since the neutron monitor increase had entirely disappeared by the time of rocket 1016.

Table 10

Intensity of Protons with Energies Greater than 2 Mev During the November, 1960, Event

Time (U.T.), Date	Rocket Number	Intensity above 2 Mev $\left(\frac{\text{particles}}{\text{cm}^2 \text{ sec ster}}\right)$	
1648, Nov. 12	1024	30,500	+150 -10%
2330, Nov. 12	1015	62,000	
1600, Nov. 13	1016	63,500	

The absence of particles with energies below 5 ± 1 Mev found by rocket 1016 is a very interesting result, and may be connected with the fact that the rocket was fired immediately after the large negative excursion of the magnetic field observed at Fredericksburg, Virginia (see Figure 28).

The November event can be interpreted within the framework of the ideas of Gold (Reference 29). In his view a disturbance on the sun, not necessarily one resulting in the acceleration of particles, may drag out the lines of force of the sun's field, forming a tongue, or "bottle". If the acceleration process occurs at the point of origin of this elongated field, particles can be trapped within it for some time, and if the earth enters the region, a solar proton event is observed. If acceleration occurs at some other point, then any particles which can enter the region may be trapped by it, but first they must travel in the local field region of the sun to the base of the bottle.

On this view there was a bottle, caused by an earlier flare, on the way toward the earth on November 2. When particle acceleration took place, the initial increase in particle intensity observed represents leakage from the bottle, since the earth was not then inside it. The "step" represents the entry of the earth; and a corresponding increase in intensity took place. The Forbush decrease occurring at the time of the step, confirms the correctness of this general picture, since it is supposed to occur when the

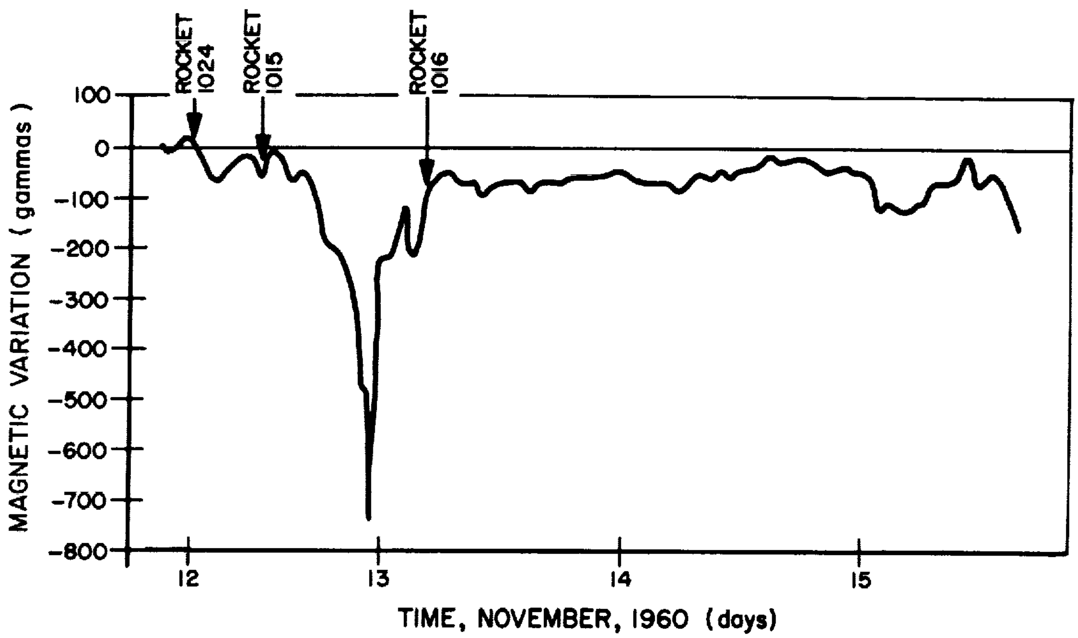

Figure 28 - Magnetic observations during November, 1960, at Fredericksburg, Virginia

earth is shielded from galactic radiation by the magnetic walls of the bottle. As McCracken (Reference 30) and others have shown, these ideas are capable of introducing a considerable simplification into the classification of cosmic ray increases. "Sharp risers", like the May 4, 1960, event where the intensity increases in a very short time and where there are marked impact zones and anisotropy, represent cases where the earth is already inside the bottle at the time of the increase. "Slow risers", which show isotropic intensity and and absence of impact zone effects, correspond to situations in which the protons must diffuse out of the walls of the bottle before reaching the earth.

It can be demonstrated that the impact zones which occur in the first situation correspond to a source direction about 50 to 60 degrees west of that of the sun, which is thought to be due to the dragging of the field by solar rotation. The principal objection which can be raised to these ideas is that of Parker, who finds it difficult to supply the energy necessary to project the field, which must travel in the form of a shock wave. The Forbush decrease is probably the phenomenon which will be the deciding factor in judging such theories.

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G-169

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